

EVALUATION OF AERODYNAMIC STABILITY FOR INCHEON CABLE-STAYED BRIDGE

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Abstract

The Incheon Bridge consists of a cable-stayed bridge and its approach bridges. In order to investigate the aerodynamic stabilities of this cable-stayed bridge, wind tunnel tests using sectional models and aeroelastic models are conducted. Additionally, flutter and gust response analyses using 3-Dimensional analytical model are carried out to check stability against flutter and gust phenomena. The analytical models take account of the geometric stiffness due to static wind loading acting on the bridge. The results of wind tunnel tests and aeroelastic analyses at completion and under construction confirmed that the bridge has adequate stability for wind-induced vibrations.

INTRODUCTION

The Incheon Bridge with a total length of approximately 18.2km includes cable-stayed bridge with a 800m-long center span, two 260m-long mid-spans, and two 80m-long side-spans. Since this long cable-stayed bridge is highly flexible, it is necessary for its aerodynamic characteristics to be thoroughly examined. Therefore a series of wind tunnel studies using both the physical models and the numerical models of Incheon Cable-Stayed Bridge were carried out for the purpose of investigating its wind resisting behavior during construction and after completion.

Initially, section model tests in both uniform and turbulent flow, with appropriate levels of damping, were carried out with angles of attack between $\pm 5^\circ$. These tests were used to refine the details of the bridge section to achieve optimum aerodynamic performance, to meet the aerodynamic criteria and to investigate the effect of turbulence on any instability detected. Drag, lift and pitching moment curves were measured on the section model.

Aeroelastic models of both the full bridge and the freestanding pylon were tested for aerodynamic

stability and also for wind forces in the completed and partially completed bridge.

During the pylon tests, the base shears normal and parallel to the span and corresponding moments were measured in each leg. In addition, accelerations at the top of the tower were measured normal and parallel to the span. The tests were carried out for wind azimuths from 0 degrees through 90 degrees and on the completed tower as well as on the tower modeled in its most critical interim stage. In order to check stability against flutter for the completed bridge as well as the bridge under construction, flutter analysis were carried out using FEM analytical model. Unsteady and steady aerodynamic forces had been measured by wind tunnel tests using bridge section model and eigenvalue analysis and wind-induced static displacement analysis had been also carried out before conducting flutter analysis.

In order to check stability against gust response for the completed bridge as well as the bridge under construction, buffeting analysis were carried out using FEM analytical model. Steady aerodynamic forces (static wind forces) had been measured by wind tunnel tests using bridge section model before conducting buffeting analysis.

ASSESSMENT CRITERIA

Aerodynamic stability of the Incheon Bridge was carried out following the codes listed below:

- MOCT: Project Performance Requirements (PPR)
- KODA: Concessionaire Supplementary Requirements (CSR)
- MOCT: Korean Highway Bridge Design Code (KBDC)

Stability Criteria for Flutter

Based on CSR, the onset of high-speed aerodynamic instability of the full bridge should not occur for wind velocities less than 72 m/s in horizontal smooth airflow, i.e. zero angle of attack. The minimum critical velocities required for vertically inclined winds are defined in Figure 1. The minimum critical velocity for the partially erected bridge is 64 m/s with corresponding reductions for vertically inclined wind. The minimum critical velocities for both the completed bridge and bridge of erection stage are listed in Table 1.

Comfort Criteria for Vortex-Induced Oscillations

Based on PPR and the ASCE comfort criteria¹, the acceptance criteria for low speed vibrations in the completed bridge are for peak vertical accelerations of the bridge deck to be less than 5% of the gravitational acceleration. This requirement should be satisfied for wind speeds up to 20 m/s. The comfort criteria do not apply for wind speeds exceeding 20 m/s.

The acceleration criteria can be converted into deflection criteria based on the frequency of vibration. For torsional vortex shedding, the criteria are based upon vertical displacement occurring at the center of the 3rd traffic lane (located 10.7m away from the deck's center).

TABLE 1 Minimum Critical Velocities for Flutter at Deck Height

Angle of Attack	0°	±2.5°	±5°
Completed Stage	72 m/s	58 m/s	36 m/s
Erection Stage	64 m/s	51.2 m/s	32 m/s

TABLE 2 Comport criteria for the completed bridge

Mode	Acceleration	Deflection
Vertical Bending	50 gal	27.5 cm
Torsion	50 gal	0.2149 deg *

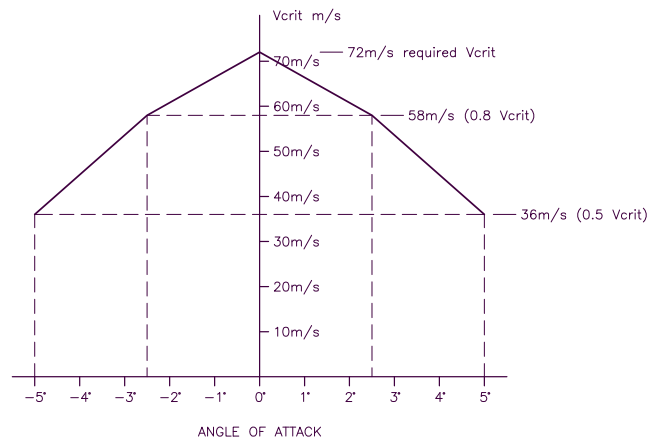


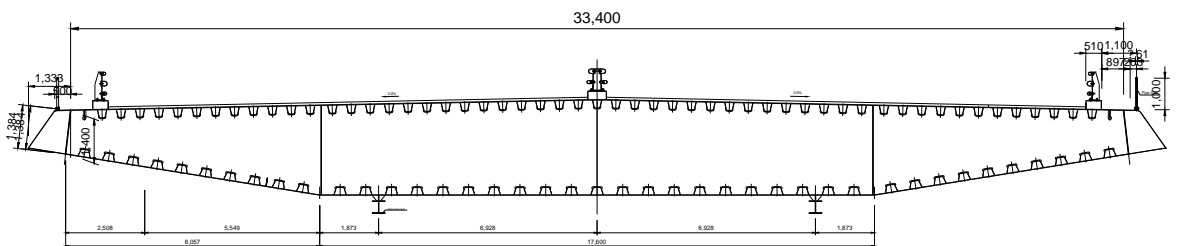
FIGURE 1 –Critical Velocity relative to Angle of Attack

BRIDGE DECK SECTION MODEL TEST

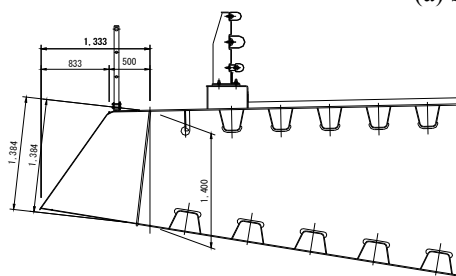
The shape of girder section which is most efficient for stabilizing aerodynamic behavior was selected by a series of section model tests using a bridge deck section model. The tests were conducted for the bridge not only after completion, but also at two erection stages, just before closing of the center span and just before closing of the side span. The section model tests were carried out using deck section models of 1/100 scale and 1/50 scale in Eiffel-type open wind tunnels.

Wind tunnels and experimental apparatus

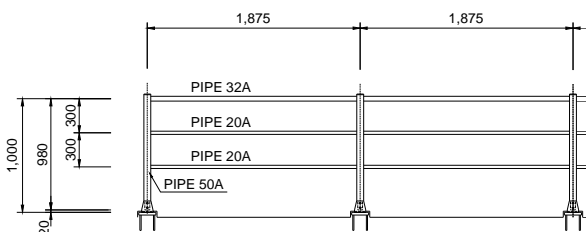
The section model tests using 1/100 scale-models were conducted at the wind tunnel (test section size: 1.0m width, 1.5m height, 6m length) of TESolution Co., Ltd. (TESolution). The wind speed range is 0.3m/s~22.5m/s. Based upon the results of the preliminary vibration test with original girder section model, the girder section was equipped with fairing and modified safety railing in order to improve the aerodynamic stability of bridge. To check Reynolds number effect and confirm the aerodynamic stability of bridge, section model tests using 1/50 scale-models were conducted at the wind tunnel of Ishikawajima-Harima Heavy Industries Co., Ltd. (IHI). In comparison between 1/100 model tests and 1/50 model tests, the aerodynamic behaviors of bridge drawn from each scale-model tests were proved to be very similar. Some slight differences might be caused by the differences in the experimental conditions like as flow condition, damping condition, and so on.



(a) Shape of improved section



(b) Fairing



(c) Safety railing

FIGURE 2 – Improved girder section

Wind-induced vibrations

The section model of bridge deck was spring-supported in two degrees of freedom of the vertical bending and torsional mode and was subjected to a vibration test as shown in Figure 3. The angle of attack (AOA) was varied from -5° to $+5^\circ$, and it is defined nose-up positive. The structural damping (logarithmic decrement) δ was set to approximately 0.02.

Figure 4 shows the response for the completed bridge in smooth flow as a result of the bridge deck sectional model test. As results of tests for vertical bending mode at attack angle $+5^\circ$, vortex shedding having maximum displacement of 16cm occurred at wind speed of 15m/s. As results of tests for torsional mode at attack angle $+5^\circ$, vortex shedding having the maximum displacement of 33cm occurred at a wind speed of 24m/s, and flutter occurred at wind speed of 75m/s. Vortex-induced excitation of the vertical bending mode occurs in the full-scale wind speed range from 13 to 15m/s. In Korea, 50gal is used as the allowable acceleration in many cases, and if converted into displacement, the allowable amplitude is 0.275m. The response value of vortex-induced excitation observed in the test was below the allowable limit. In the torsional mode, the comfort criteria do not apply because vortex-induced excitation occurs at wind speeds exceeding 20 m/s, and the onset wind velocity of torsional flutter exceeded the required critical velocity in all AOA cases.

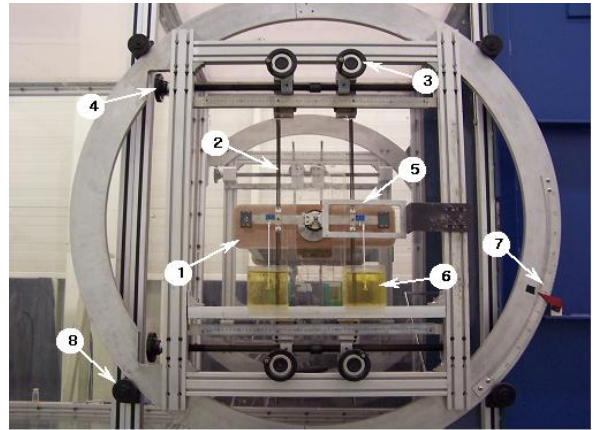


FIGURE 3 – Spring suspension system

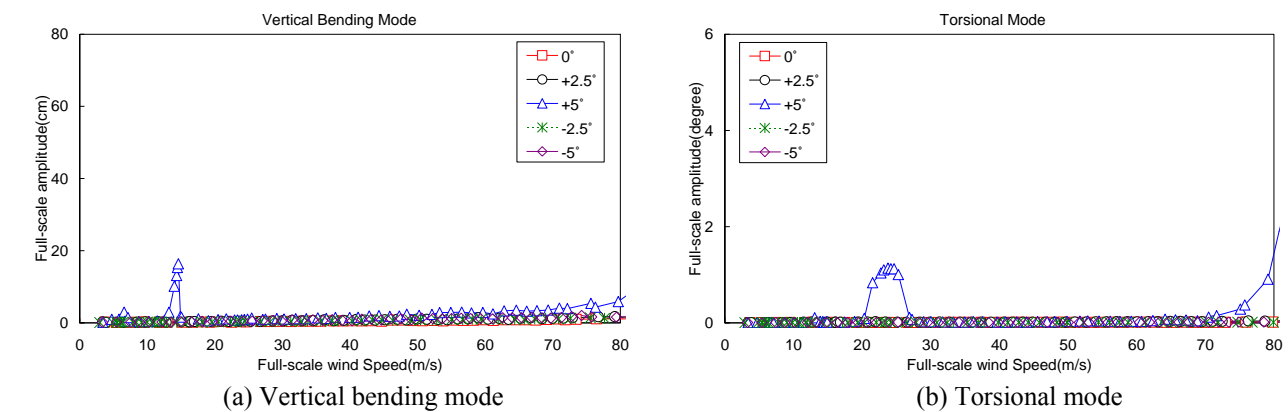


FIGURE 4 – Velocity-amplitude graph (at completion, in smooth flow)

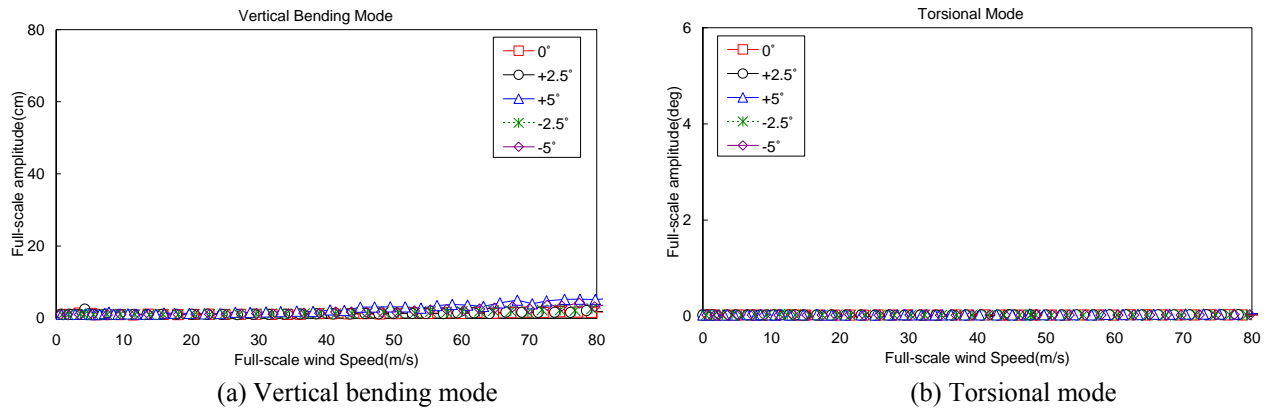


FIGURE 5 – Velocity-amplitude graph (at erection stage, in smooth flow)

Steady aerodynamic force coefficients

Using two 3-components balances, tests were conducted to measure the steady aerodynamic forces and moment. Drag force coefficient C_D , lift force coefficient C_L , and pitching moment coefficient C_M are defined by following equations. The steady aerodynamic force coefficients were measured at the range of AOA= $-10^\circ \sim +10^\circ$ for the completed stage and the erection stage, and theses are shown in Figure 7.

$$C_D = F_D / (0.5 \rho U^2 D l)$$

$$C_L = F_L / (0.5 \rho U^2 B l)$$

$$C_M = F_M / (0.5 \rho U^2 B^2 l)$$

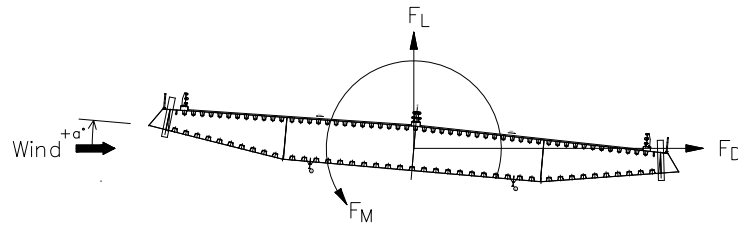


FIGURE 6 – Steady aerodynamic force on a bridge deck (Structural axis)

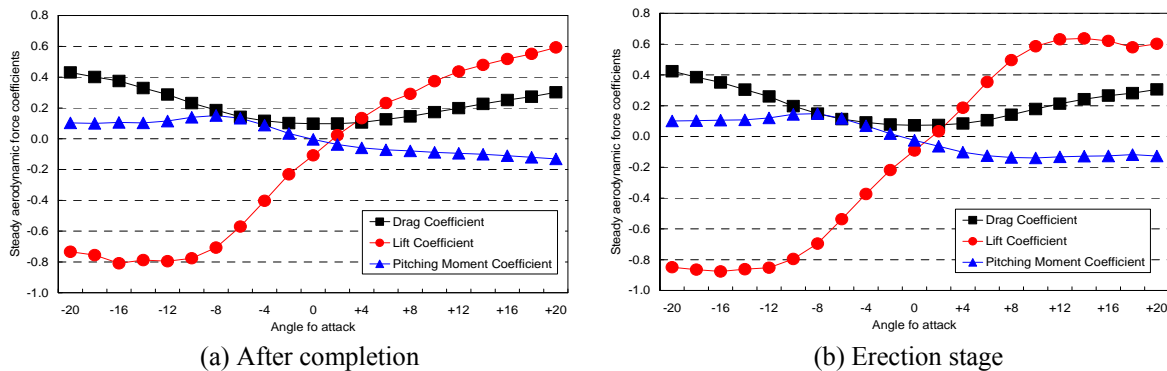


FIGURE 7 – Steady aerodynamic force coefficients

AEROELASTIC MODE TEST FOR PYLON

The aeroelastic model(scale=1/100) tests for free-standing pylon were performed at Industrial Aerodynamics Wind Tunnel of Ishikawajima-Harima Heavy Industries Co., Ltd. (IHI) in Yokohama:

- Working section: 6.0m wide \times 3.0m high \times 24m long
- Maximum wind velocity: 15m/s

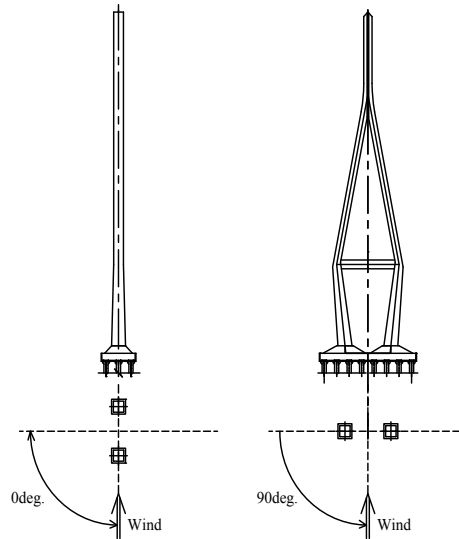


FIGURE 8 –Definition of wind direction

The tests were carried out in turbulent boundary layer and turbulent characteristics of the boundary layer were found that the turbulence intensities of the generated flow meet the required by the Specification approximately. On the other hand, the length scale of generated flow is smaller than that of the Specification where wind flow at the bridge site has pretty large turbulence scale in comparison to typical atmospheric boundary layer. Wind direction is varied from 0° to $+90^\circ$, as shown in Figure 7. In verification of the pylon model, since it is confirmed that dynamic similarities

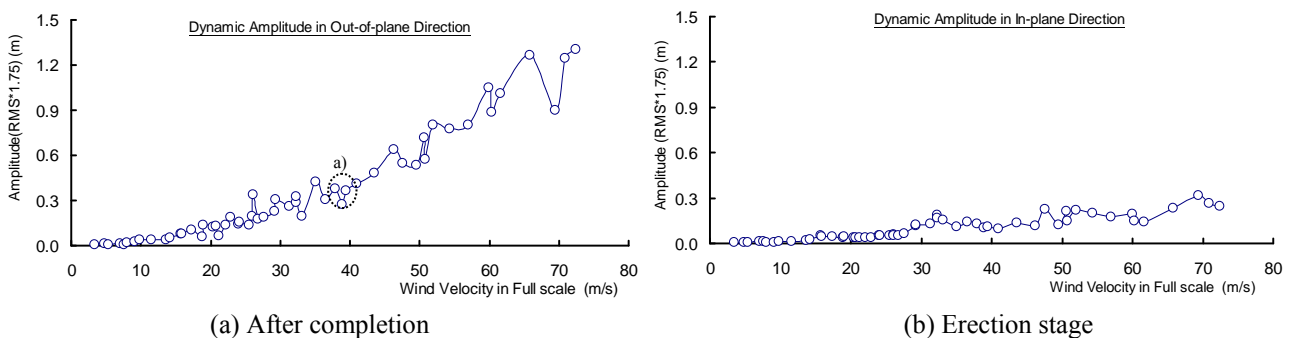


FIGURE 9 – Response at the top of pylon (Wind direction = $+90^\circ$)

of the model are assured, the reliability of vibration test results is considered to be established. Maximum dynamic displacement was observed in boundary layer flow in the wind direction of 90° . Wind induced dynamic displacements as functions of wind velocity (V-A diagram) are illustrated in Figure 9. In these figures, the velocities were obtained at the deck height and the dynamic response amplitudes at the top of pylon were expressed in 1.75 times of R.M.S. amplitude.

FLUTTER ANALYSIS

Unsteady aerodynamic force coefficients

Forced vibration test was conducted to measure unsteady aerodynamic forces acting on section model at “Structure Stability Wind Tunnel” of Ishikawajima-Harima Heavy Industries Co., Ltd. (IHI) Research Institute at Yokohama in Japan. The test section is 1.5m width 2.5m height and 8m length. The wind



FIGURE 10 – Forced vibration equipment

speed range is 0.5m/s-20m/s. Unsteady aerodynamic forces (drag, lift and moment) were measured in the wind tunnel test. They were measured using the two 3-components balances attached at both ends of the sectional model as shown in Figure 10. Forced vibration method was adopted with either heaving motion or torsional motion. Measurement of flutter derivatives by imposed sinusoidal motion (model scale 1/50, heaving amplitude of $B/100 = 6.68\text{mm}$ and pitching of 1 deg.) were conducted at AOA=-5.0, -2.5, 0, 2.5, 5.0 degrees. In this investigation, the flutter derivatives of the bridge deck defined in Eq.(1),(2),(3) were measured. The results at angles of -5.0, 0, +5.0 degrees are graphed, the other results (-2.5, +2.5 degrees) are omitted. Figure 11 provides a comparison between the measurements of flutter derivatives and theoretical values derived from a flat plate (Theodorsen function) at completion stage.

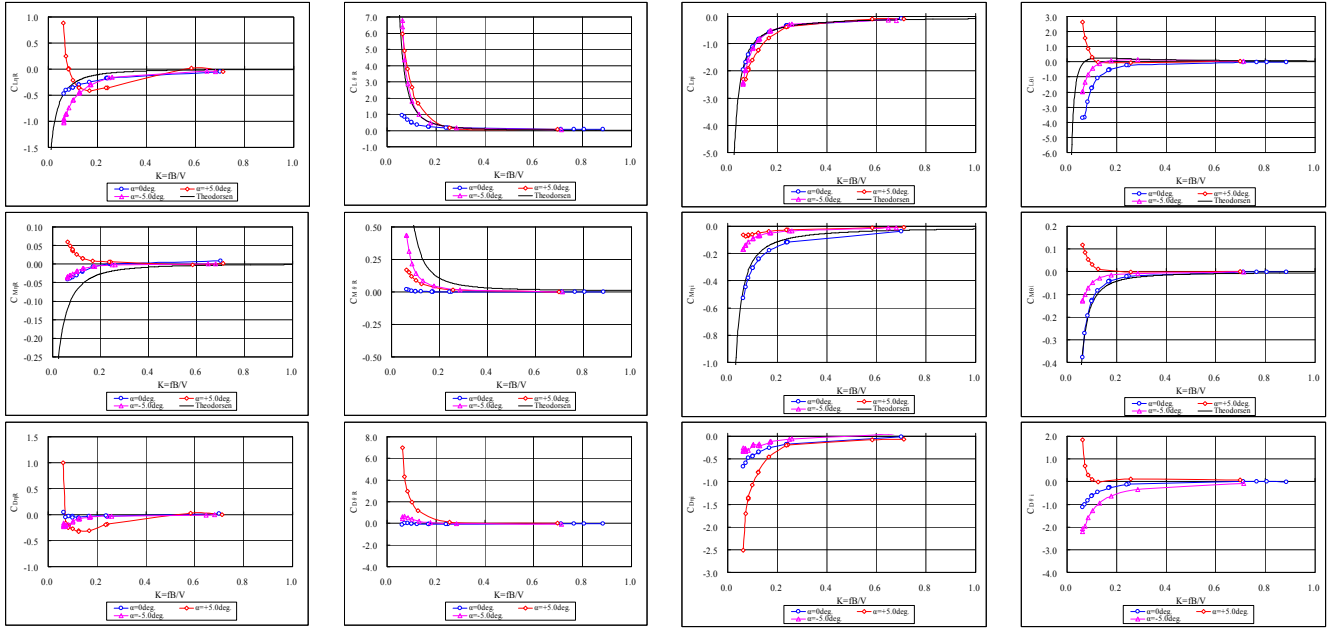


FIGURE 11 – Unsteady aerodynamic coefficients at completion stage (-5.0, 0, +5.0deg.)

$$L = \pi \rho B^3 \omega^2 \left\{ (C_{L\eta R} + i \cdot C_{L\eta i}) \frac{\eta}{B} + (C_{L\theta R} + i \cdot C_{L\theta i}) \theta + (C_{L\zeta R} + i \cdot C_{L\zeta i}) \frac{\zeta}{B} \right\} \quad (1)$$

$$M = \pi \rho B^4 \omega^2 \left\{ (C_{M\eta R} + i \cdot C_{M\eta i}) \frac{\eta}{B} + (C_{M\theta R} + i \cdot C_{M\theta i}) \theta + (C_{M\zeta R} + i \cdot C_{M\zeta i}) \frac{\zeta}{B} \right\} \quad (2)$$

$$D = \pi \rho B^2 A_n \omega^2 \left\{ (C_{D\eta R} + i \cdot C_{D\eta i}) \frac{\eta}{B} + (C_{D\theta R} + i \cdot C_{D\theta i}) \theta + (C_{D\zeta R} + i \cdot C_{D\zeta i}) \frac{\zeta}{B} \right\} \quad (3)$$

where, L = unsteady aerodynamic lift, M = unsteady aerodynamic moment, D = unsteady aerodynamic drag, ω = circular frequency, $C_{F\eta R} \sim C_{F\theta i} =$ measured flutter derivatives ($F=L, M, D$)

Flutter instability

The program used for flutter analysis has the outstanding feature that the natural frequencies and mode shapes are obtained at each wind speed where flutter analysis is carried out. This means that natural frequencies and mode shapes are being taken account of the geometric stiffness due to static wind loading acting on the bridge. In this flutter analysis, the number of vibration modes to be used in calculation is up to the 38th modes. Figure 12 illustrates calculated response dampings at completion stage. Any instability is not observed as far as we investigated. In the case of free vibration test with

wind direction $\alpha = +5.0$ deg. at completion stage, the torsional flutter instability was occurred at about 75m/s in full-scale wind velocity, bBut according to the flutter analysis at $\alpha = 0, \pm 2.5$ deg. at completion stage, the flutter instability seems to be not occurred up to 100m/s in full-scale wind velocity.

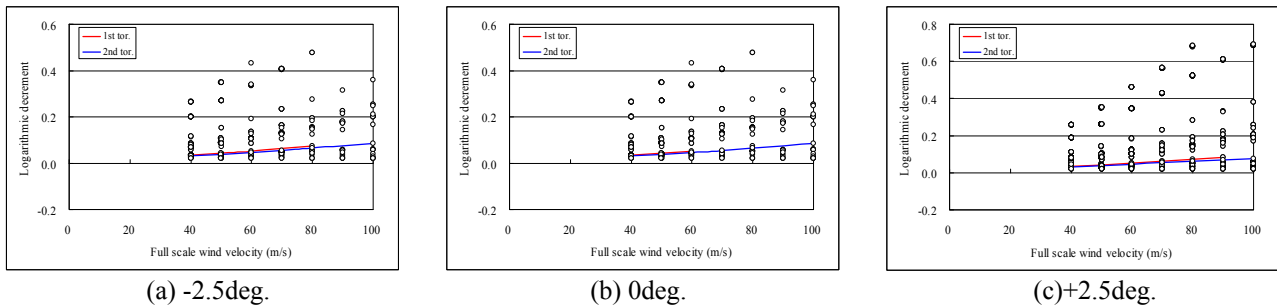


FIGURE 12 – Aerodynamic damping at completion stage

GUST RESPONSE ANALYSIS

Gust response is random vibration of a bridge caused by turbulence of an oncoming flow. Its vibration amplitude has a tendency to develop in almost proportion to a square of wind speed. Gust response is treated as a fluctuating wind loading problem in the wind-resistant design of long-span bridges. Expectation of the maximum wind loading based on the random theory is applied to the structural design. Evaluation of gust response and the maximum wind loading of a long-span bridge in Korea have been based on the Davenport theory. This is due to the simplicity of analysis and necessity of statistical values such as the maximum and R.M.S. amplitudes in a design stage. The program used for gust response analysis has the following outstanding feature: The natural frequencies and mode shapes are obtained at each wind speed where gust response analysis is carried out. This means that natural frequencies and mode shapes are being taken account of the geometric stiffness due to static wind loading acting on the bridge. Also, wind loading is calculated using aerodynamic static force coefficients for each deck member of the mathematical model after deformation due to static wind loading. For other research organizations, gust response analysis is usually conducted without taking account of the geometric stiffness and the change of aerodynamic static force coefficients due to deformation of the deck by static wind loading. Therefore, we can make a more precise wind engineering judgment against gust response of the Incheon Bridge by using the gust response analysis. As the result of gust response analysis, the dynamic response amplitudes of the girder are shown in Figure 13.

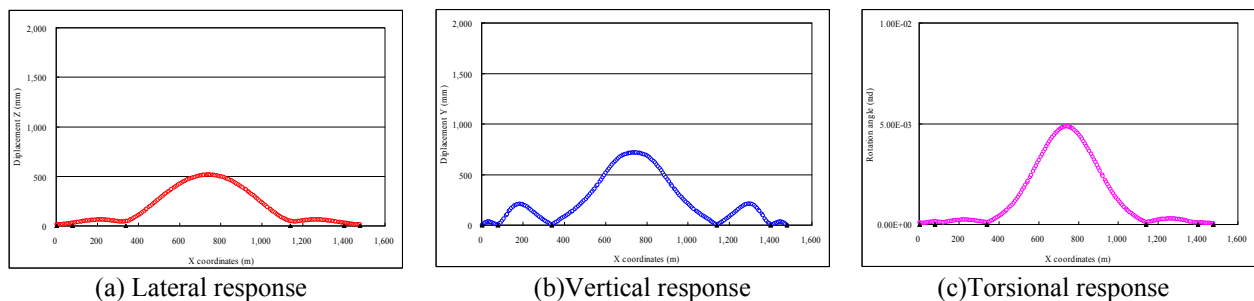


FIGURE 13 – Deformation and rotation angle at completion stage

AEROELASTIC MODEL TEST FOR FULL BRIDGE

The aeroelastic model tests for full bridge were carried out in the 1.5MW wind tunnels at Monash University in Australia. The test section is 12m width, 4m height and 20m length. The wind speed range is 0.5m/s-15m/s. The tunnel wind speed can be increased by approximately 0.1m/s intervals. An active mechanical turbulence generator can be installed in the lower return circuit to produce turbulence of very large turbulence integral length scale necessary for a 1/150 scale modeling of natural boundary layer wind in the test working section for aeroelastic full bridge model tests.

The lateral and vertical displacements and the rotations of the bridge deck at various locations were measured with strain gauged displacement units calibrated with laser displacement sensors.

The accelerations at the top of the pylon tower were measured using piezoelectric accelerometers. The static and dynamic responses are seen to increase with increasing wind speed. For the bridge at completed stage, at a mean wind speed of 54.3 m/s at the deck height of 83m for wind direction normal to the deck spanwise axis for the turbulent wind flow conditions, the maximum vertical displacement at the centre of the bridge deck was measured to be 0.8m with a damping of 0.02 (logarithmic decrement).



FIGURE 14 – 1/150 scale aeroelastic model
(at completed stage)

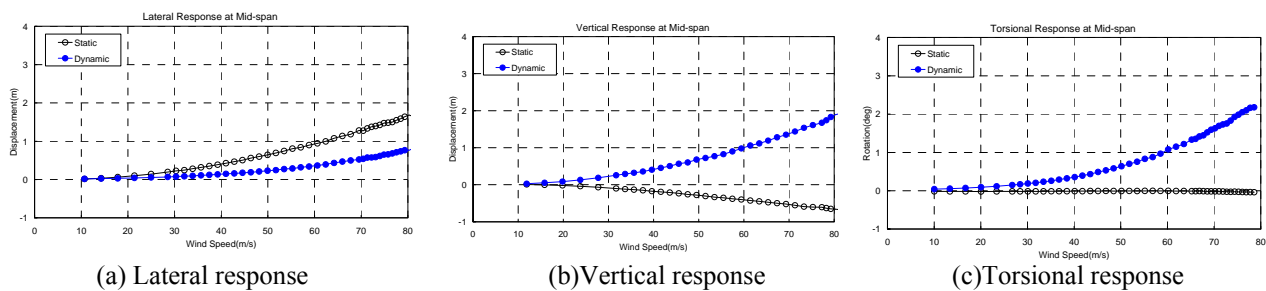


FIGURE 17 – Deformation & rotation angle of the girder (Mid-span)

CONCLUSION

The aerodynamic stabilities of the Incheon Bridge at completion and under construction were evaluated by wind tunnel tests using sectional models and aeroelastic models. Flutter and gust response analyses using 3-Dimensional analytical model were conducted. As a result, it was found that the safety is sufficient against wind-induced vibrations. Considering the wind characteristics at the site, moreover, a vibration-suppression effect can be expected from the wind turbulence, and this was verified by a test in turbulence boundary layer flow

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